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$J/\psi + \gamma$ production at the Tevatron Energy

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ABSTRACT

We study the process $\bar{p}p \rightarrow J/\psi + \gamma + X$ at the Tevatron energy ($\sqrt{s} = 1.8$ TeV). The perturbative QCD contributions to this process from the gluon-fusion and the fragmentation mechanisms are computed. For the entire range of p_T that can be probed at the Tevatron, the fusion contribution is found to be dominant. Consequently the QCD prediction for this process has better precision than the purely hadronic production of J/ψ . An experimental study of this process at the Tevatron will help to clarify several aspects of quarkonium production at large p_T .

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The production of quarkonia at large p_T is usually described by the parton-fusion mechanism in the framework of the colour-singlet model [1, 2, 3]. In this model, the wave-function at the origin for a S -wave (or its derivative for a P -wave) quarkonium is convoluted with the cross-section for producing a heavy quark pair with the proper spin, parity and charge-conjugation assignments. The wave-function $|R_0(0)|^2$ can be estimated from the S -wave quarkonium decay widths within an uncertainty of $\sim 30\%$, arising from relativistic correction [4, 5]. The corresponding uncertainty in the estimate of the derivative of the wave-function $|R'_1(0)|^2$ from P -wave quarkonium decay is much larger, since the NLO correction for this case is not yet available [4, 5, 6]. This uncertainty propagates into the hadroproduction cross-section of J/ψ , which is dominated by the $\chi \rightarrow \psi + \gamma$ decay contributions. Together with the uncertainty from the choice of QCD scale in the $c\bar{c}$ pair production, one can predict the J/ψ hadroproduction cross-section to within a factor of ~ 3 . Within this normalisation uncertainty, the colour singlet model prediction agrees with the J/ψ hadroproduction data from fixed-target and ISR experiments over a reasonable range of p_T [2, 5, 7, 8]. A comprehensive account of the model prediction and comparison with these data is given in [5].

At higher energies where b -quark production becomes important, the decay of b quarks is a mechanism that contributes to J/ψ production, in addition to the parton-fusion mechanism of the colour-singlet model [4]. Recently, the CDF experiment studied the large- p_T J/ψ production at the Tevatron collider [9] and, using the secondary vertex information, separated out the b -quark decay contribution. The remaining J/ψ 's are presumably produced directly by the fusion mechanism, but the CDF experiment found that the cross-section is an order of magnitude larger than that predicted by the fusion mechanism of the colour-singlet model. Even if one takes into account the above mentioned normalisation uncertainty in the theoretical predictions, it does not suffice to restore agreement with the CDF data.

The anomalously large cross-section measured in the CDF experiment – the CDF effect – indicates that there is a new mechanism through which J/ψ production takes place at large p_T . At high-energy colliders, where gluons and charm quarks are copiously produced, the fragmentation of these particles into J/ψ has been suggested as an important mechanism for large- p_T J/ψ production [10]. The validity of this suggestion is borne out by the explicit computation of the fusion and fragmentation contributions for the Tevatron energy, presented in Refs. [11, 12, 13]. In these papers, it was shown that the fragmentation contribution is the dominant contribution at the Tevatron energy; and together with the fusion contribution it can explain the large cross-section measured by the CDF experiment to within a factor of 2-3. The largest contribution comes from gluons fragmenting into χ 's, which subsequently decay into J/ψ 's. In Ref. [11], the energy dependence of the fragmentation and fusion contributions was studied as well. It was shown that at ISR energies the fusion contribution

dominates over the p_T range of interest, although the inclusion of the fragmentation contribution helps to improve the quantitative agreement with the ISR data.

In Refs. [11, 12], the production of ψ' by fragmentation was also studied. Unlike J/ψ production, ψ' production does not involve the P -state contribution. Consequently, the fragmentation contribution is comparatively smaller. The total predicted ψ' cross-section is at least an order of magnitude smaller than the cross-section measured by CDF. This large discrepancy with ψ' data seems to indicate a large contribution to the S -wave quarkonium production from a still unknown mechanism. As noted in [11, 12], this will show up in a larger enhancement of the ψ' cross-section than the J/ψ . Whatever be the source of this new contribution, it is important to probe it phenomenologically through other processes of quarkonium production at large p_T . In this note, we point out that the production of a large- p_T J/ψ with an associated photon will serve as a very interesting probe for such mechanisms of quarkonium production.

As we shall see below, the associated production of a large- p_T J/ψ with a photon has three distinctive features in comparison with the purely hadronic J/ψ production discussed above. 1) The fusion contribution to this process dominates over the fragmentation for the entire p_T range of interest at the Tevatron energy. 2) The fusion contribution comes entirely from the direct production of the S -state. 3) The S -state wave function $|R_0(0)|^2$ is known to reasonable precision; and besides the uncertainty associated with the QCD scale is much smaller here than the purely hadronic process. In short, the dominant contribution to this process comes from the direct production of the S -state, which can be predicted to a reasonable precision. Thus it is well suited to probe for an anomalous enhancement of the S -wave quarkonium production at large- p_T .

In recent years, there have been several discussions of associated production of a J/ψ and a photon in hadron-hadron experiments [14, 15, 16, 17]. This production of a J/ψ - γ pair can also take place at HERA [14, 18], through resolved photon processes. In the framework of the colour-singlet model, the production of a J/ψ and an associated photon, proceeds through the following subprocess:

$$g + g \rightarrow J/\psi + \gamma. \quad (1)$$

C -invariance forbids a χ coupling to two gluons and a photon; so a χ cannot be produced *via* the above subprocess. Of course, the χ contribution through $gg \rightarrow \chi \rightarrow J/\psi + \gamma$ is possible; but this will contribute to low- p_T J/ψ 's and γ 's, and can be eliminated by a p_T or invariant mass cut. Therefore, large- p_T $J/\psi + \gamma$ production through gluon fusion involves only the S -wave resonance.

In addition to the gluon-fusion contribution, one expects a fragmentation contribution to the associated production of $J/\psi + \gamma$ at large- p_T . The fragmentation

contribution to J/ψ is expected to come mainly from the gluon and charm-quark jets [10, 11, 12, 13]. Thus the basic process of interest is the associated production of a large- p_T photon with a gluon (or a charm quark), followed by the fragmentation of the latter into J/ψ either directly or via the χ 's. Consequently the fragmentation contribution involves both S and P states. Another distinctive feature of the fragmentation contribution is the emergence of the J/ψ along with the other jet fragments. Thus in principle one could distinguish it from the fusion process (1) by requiring either J/ψ isolation or p_T balancing between J/ψ and γ . It would be hard to implement this in practice, however, since the J/ψ is expected to carry away the bulk ($\sim 70\%$) of the jet momentum [12]. Therefore one has to deal with the sum of the fusion and fragmentation contributions.

There is another source of $J/\psi + \gamma$ production at large- p_T – i.e. the associated production of a large- p_T J/ψ with a hadron jet, followed by the fragmentation of the latter into a hard photon [19, 20, 21]. However this process can be substantially reduced by the standard isolation cut on γ used in the direct photon experiments. It was noted in [21] that even with the isolation cut one should not neglect this fragmentation contribution while dealing with the NLO correction to direct photon production. In the present work we shall work with the lowest-order direct photon production cross-section and hence neglect the contribution from photons produced via fragmentation.

Finally, we wish to make an observation here concerning the model-dependence of the fusion contribution. We will use the colour-singlet model of J/ψ production in this work; but there exists another model of J/ψ production – the semi-local duality model [22]. In this model, the J/ψ cross-section is given by integrating the open $c\bar{c}$ cross-section between $2m_c$ and the open $c\bar{c}$ production threshold and multiplying by a normalisation factor, which is not specified by the model but has to be determined by comparing with data. In this model, the $c\bar{c}$ pair produced in the hard-scattering is not required to be a colour-singlet, neither is a projection to the quarkonium quantum numbers required. The colour and quantum numbers are assumed to rearrange themselves appropriately, in the process of soft-gluon emission. Consequently, in this model, the $q\bar{q}$ -fusion production of $J/\psi + \gamma$ is allowed, in addition to the gluon-gluon fusion [16]. However, at the large energies of our present interest the gg fusion is expected to dominate in the duality model, so that the predictions of the two models would not be significantly different.

The subprocess cross-section for $J/\psi + \gamma$ production in the colour-singlet model is given as

$$\frac{d\sigma}{d\hat{t}}(gg \rightarrow J/\psi + \gamma) = \frac{16\pi\alpha\alpha_s^2 M |R_0(0)|^2}{27\hat{s}^2} \left[\frac{\hat{s}^2}{(\hat{t} - M^2)^2(\hat{u} - M^2)^2} \right]$$

$$\left. + \frac{\hat{t}^2}{(\hat{s} - M^2)^2(\hat{u} - M^2)^2} + \frac{\hat{u}^2}{(\hat{t} - M^2)^2(\hat{s} - M^2)^2} \right], \quad (2)$$

where \hat{s} , \hat{t} and \hat{u} are the usual Mandelstam variables and M is the mass of the J/ψ . To obtain the hadronic p_T distribution, this subprocess cross-section is folded in with the gluon densities, as follows:

$$\begin{aligned} \frac{d\sigma}{dp_T}(AB \rightarrow J/\psi + \gamma) = \\ \sum \int dy \int dx_1 x_1 g_A(x_1) x_2 g_B(x_2) \frac{4p_T}{2x_1 - \bar{x}_T e^y} \frac{d\hat{\sigma}}{d\hat{t}}(gg \rightarrow J/\psi + \gamma). \end{aligned} \quad (3)$$

In the above equation, g_A and g_B are the gluon distributions in A and B , x_1 and x_2 are the respective momentum fractions. Energy-momentum conservation determines x_2 to be

$$x_2 = \frac{x_1 \bar{x}_T e^{-y} - 2\tau}{2x_1 - \bar{x}_T e^y}, \quad (4)$$

where $\tau = M^2/s$, \sqrt{s} the centre-of-mass energy, and y the rapidity at which the J/ψ is produced. We also have

$$\bar{x}_T = \sqrt{x_T^2 + 4\tau} \equiv \frac{2M_T}{\sqrt{s}}, \quad x_T = \frac{2p_T}{\sqrt{s}}. \quad (5)$$

As discussed above, in addition to the fusion process there is a contribution to $J/\psi + \gamma$ production from the fragmentation of gluons and charm quarks. At lowest order, the subprocesses that give rise to a parton at large p_T with an associated photon are the usual direct photon subprocesses:

$$\begin{aligned} q + \bar{q} &\rightarrow g + \gamma \\ Q + g &\rightarrow Q + \gamma, \end{aligned} \quad (6)$$

where we have used Q to denote the charm quark, and the charm-quark density in the initial state is that generated by the Q^2 evolution of the structure functions. Assuming factorisation, the fragmentation contribution to the $J/\psi + \gamma$ cross-section can be written as

$$d\sigma(AB \rightarrow (J/\psi, \chi_i) + \gamma + X) = \sum \int_0^1 dz \, d\sigma(AB \rightarrow c + \gamma + X) D_{c \rightarrow (J/\psi, \chi_i)}(z, \mu), \quad (7)$$

where $d\sigma(AB \rightarrow c + \gamma + X)$ is the hard-scattering cross-section for the production of a parton (denoted by c) in association with a photon, $D(z, \mu)$ is the fragmentation function specifying the fragmentation of parton (gluon or charm quark) into the required charmonium state, and z , as usual, is the fraction of the momentum of the parent

parton carried by the charmonium state. The sum in the above equation runs over all contributing partons. The fragmentation function is computed perturbatively at an initial scale μ_0 , which is of the order of m_c . It is then evolved to the scale typical of the fragmenting parton, which is of the order of p_T/z , using the Altarelli-Parisi equation. The full set of initial fragmentation functions needed to obtain the J/ψ and the χ contributions have now been computed. They are $D_{g \rightarrow J/\psi}$ [10], $D_{g \rightarrow \chi}$ [23], $D_{c \rightarrow \psi}$ [24] and $D_{c \rightarrow \chi}$ [25, 26].

For the fragmentation process, the cross-section is given by a formula similar to Eq. 3 but with an extra integration over z , or equivalently over x_2 . We have

$$\frac{d\sigma}{dp_T}(AB \rightarrow (J/\psi, \chi_i) + \gamma X) = \sum \int dy dx_1 dx_2 G_{a/A}(x_1) G_{b/B}(x_2) D_{c \rightarrow (J/\psi, \chi_i)}(z) \frac{2p_T}{z} \frac{d\hat{\sigma}}{d\hat{t}}(ab \rightarrow c + \gamma), \quad (8)$$

with z given by

$$z = \frac{\bar{x}_T}{2} \left(\frac{e^{-y}}{x_2} + \frac{e^y}{x_1} \right). \quad (9)$$

For $d\hat{\sigma}/d\hat{t}(ab \rightarrow c + \gamma)$, we have used the lowest-order direct photon cross-sections [20].

In Fig. 1, we have presented our results for the fusion and fragmentation contributions to $J/\psi + \gamma$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. We have plotted $Bd\sigma/dp_T$ as a function of p_T , integrated over a pseudo-rapidity range $|\eta| < 0.5$, where B is the J/ψ branching ratio into leptons ($B = 0.0594$). In our computations, we have used [27] the updated MRSD-' parametrizations [28] for the parton densities in the nucleon. The parton densities are evolved to a scale $Q^2 = \mu^2/4$, where μ is chosen to be M_T for the fusion case, and equal to $p_T^{g,c} = p_T/z$ for the fragmentation case. The fragmentation functions are evolved to the scale p_T/z . Another uncertainty that enters the normalisation of the predicted cross-sections is that due to the wave-function at the origin, R_0 , the derivative for the P -states, R'_1 (or equivalently H_1) and H'_8 , which is a parameter that describes the $g \rightarrow \chi$ fragmentation through a colour-octet mechanism. The last parameter is related to the infrared divergent term in the NLO correction to the P -state decay and has by far the largest uncertainty. For the parameters R_0 , H_1 and H'_8 , we have used the values quoted in Refs. [10, 23]: $R_0^2 = 0.8 \text{ GeV}^3$, $H_1 = 15.0 \text{ MeV}$, $H'_8 = 3.0 \text{ MeV}$.

The fusion contribution (shown as the solid line in Fig. 1) comes entirely from the S -state production and hence depends only on R_0^2 . Being a gluon-gluon fusion process, it is seen to dominate over the whole range of p_T considered. The gluon fragmentation contribution (including $g \rightarrow J/\psi$ and $g \rightarrow \chi$ and shown as the dashed line in Fig. 1) and the charm-quark fragmentation (shown as the dotted line) are more than an order of magnitude smaller than the fusion contribution, even at the largest

values of p_T considered. These features may be contrasted with the purely hadronic J/ψ production where the gluon fragmentation dominates over fusion and both the contributions are dominated by the production of P -states [11, 12].

In Fig. 2, we show the $J/\psi + \gamma$ cross-section (i.e. the sum of the fusion and fragmentation contributions) as a function of p_T . This is shown as the solid line in Fig. 2. The cross-section is large enough to be measurable at the Tevatron. We also estimated the magnitude of the $\psi' + \gamma$ cross-section, but it turns out to be two to three orders of magnitude smaller than the $J/\psi + \gamma$ cross-section, and may be too small to be observed. We have also considered the effect of varying the scale from $\mu/2$ to 2μ on the $J/\psi + \gamma$ cross-section (the latter choice is shown as the dashed line in Fig. 2). The cross-section is remarkably stable under scale variation. This is due to a substantial compensation between the decrease of α_s and the increase of the low- x gluon distribution $g(x \simeq .01)$ in eqs. 2,3 as the scale is increased from $\mu/2$ to 2μ . As a result the QCD prediction for the dominant process of gluon fusion (1) is remarkably stable under scale variation at the Tevatron energy. The net uncertainty from the choice of scale as well as the QCD parametrisation may be roughly estimated as $\pm 40\%$. As remarked before, the uncertainty from the estimate of the corresponding wave function R_0^2 is also quite small ($\sim \pm 30\%$). Combining the two gives an overall uncertainty of $\pm 50\%$ for the predicted $J/\psi + \gamma$ cross-section of Fig. 2. Measurement of the cross-section at the Tevatron will therefore be very useful in probing for any new source of quarkonium production at large p_T . In particular an anomalous enhancement of the S -wave quarkonium production would show up here as clearly as in the purely hadronic production of ψ' if it is associated with the fusion mechanism, but not if it comes from the fragmentation.

In summary, we have analysed the associated production of a large- p_T J/ψ and γ at the Tevatron energy. The perturbative QCD predictions for the fusion and the fragmentation contributions have been computed. The fusion contribution is seen to dominate this cross-section over the entire p_T range of interest, unlike the purely hadronic production of J/ψ . More over the fusion contribution to this process comes entirely from the direct production of the S -wave quarkonium. Consequently one has a rather precise QCD prediction for this process. Experimental measurement of this cross-section will help to clarify several aspects of quarkonium production at large p_T , and in particular those related to the anomalous hadronic J/ψ and ψ' cross-sections recently reported by the CDF experiment (the CDF effect).

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Figure captions

Fig. 1 Lower figure: The cross-section $Bd\sigma/dp_T$ (integrated over the pseudorapidity range $-0.5 < \eta < 0.5$) for the process $\bar{p}p \rightarrow J/\psi + \gamma + X$ as a function of p_T at $\sqrt{s} = 1.8$ TeV. The different curves correspond to the direct production via fusion (solid line), the gluon fragmentation contribution (dashed line) and the charm-quark fragmentation term (dotted line).

Fig. 2 The scale dependence of the $J/\psi + \gamma$ cross-section as a function of p_T for $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. The solid curve in both figures is for the scale $\mu/2$ and the dashed curve is for the scale 2μ .